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Simulation of the effects of window opening and heating set-point behaviour on indoor climate and building energy performance

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SUMMARY

Simultaneous measurement of occupant behaviour, indoor and outdoor environment was carried out in 15 dwellings in Denmark during the period from January to August 2008. Based on the measurements occupant behavioural patterns were defined and implemented in the building simulation program IDA ICE. A case and a reference simulation were carried out. In the case, the behaviour patterns derived from the measurements were used while the reference used simulated behaviour patterns defined like they might have been by a consultant engineer. The simulated behaviour patterns resulted in large differences in indoor environmental variables between the two simulations. The heat consumption was more than three times as high in the case as in the reference simulation. This underlines the importance of considering the behaviour of the occupants in the design process of buildings.

KEYWORDS

Occupant behaviour, Energy, Simulation, Window opening, heating set-point

INTRODUCTION

Occupants who have the possibility to control their indoor environment have been found to be more satisfied and suffer fewer building related symptoms than occupants who are exposed to environments of which they have no control (Paciuk, 1989; Toftum, 2008; Brager et al. 2004). However, occupant behaviour varies significantly between individuals which results in large variations in the energy consumption of buildings. Because of this, it is important to take occupant interaction with the control systems into account when designing buildings.

Most building simulation programs provide possibilities of regulating the simulated environment by adjusting building control systems (opening windows, adjusting temperature set-points etc.). However, discrepancies between simulated and actual behaviour can lead to very large discrepancies between simulation results and actual energy use (Macintosh and Steemers, 2005). Thus there is a need to set up standards or guidelines to be able to compare simulation results between cases. Measurements of window opening behaviour and indoor and outdoor environmental variables in 15 Danish dwellings were used to infer the probability of opening and closing windows. Relations between thermostat heating set-point and environmental variables were also established. These relations and probabilities were implemented in the dynamic building simulation software IDA ICE and compared to a more conventional consultant approach.

METHODS

The model consisted of a single room in a single family house located in Denmark. The room had two facades facing south and east. The room had five windows (height: 1.5 m, width: 1.2 m) and two water based radiators under the windows.

The local wind pressure coefficient of the faces of the building was determined according to the ASHRAE Handbook of Fundamentals (1997). The opening areas of cracks in the outer

walls were adjusted with the aim of an average infiltration rate of 0.19 h^{-1} . This aim was based on a study by Kvistgaard et al. (1985) who found an average infiltration rate of 0.19 h^{-1} in 14 Danish dwellings.

Simulated behaviour

Two behaviour patterns were simulated: A case that simulated the behaviour patterns derived from measurements described in Andersen et al. (2009) and a reference simulation with behaviour patterns defined like they might have been by a consultant engineer.

In each time-step the probability of opening and closing a window was calculated based on the logistic regression coefficients described in Andersen et al. (2009). The probabilities were calculated based on the time of day, day in week, temperature (indoor and outdoor), indoor CO_2 concentration, relative humidity (indoor and outdoor), wind speed and solar radiation. The results of the calculations were the probability of opening/closing a window within the next 10 minutes. Like most simulation programs, IDA ICE is deterministic rather than probabilistic in nature. As a result the probability of an event had to be translated to a deterministic signal. A way of doing this is to compare the probability to a random number to determine if the event takes place or not. As the given probability is the probability of an event in the next 10 minutes, the comparison was made with a random number between 0 and 1 that changed every 10^{th} minute. The window was opened or closed if the random number was smaller than the calculated probability. Out of the five windows in the room one window in each wall was operable and opened and closed simultaneously.

The heating set-point was determined by the regression coefficients described in Andersen et al. (2009). Waterborne heaters were controlled by a p-controller with a dead band of 1°C .

The occupancy was determined by a first order Markov-chain technique described by Richardson et al. (2008). An Excel sheet provided by Richardson et al. (2008) was modified to generate yearly (instead of daily) time series of occupancy with a 10 minute resolution. This was used as input to determine the occupancy in the simulated room. When there were no occupants present (or all occupants were at sleep), the windows were closed and the heating set-point remained unchanged.

A reference simulation was made where the heating set-point was 21°C with a dead band of 2°C all year round. The windows opened if the temperature exceeded 26°C and closed again when the indoor temperature decreased below 22°C . This simulation was conducted to investigate the effects of the behaviour model by comparing with a simulated that could have been conducted by a consultant.

RESULTS OF THE BEHAVIOUR SIMULATIONS

During almost all of the time when the room was occupied, the indoor temperature was higher in the case than in the reference simulation (Figure 1). This was a result of a higher heating set-point during winter in the case simulation. In the reference simulation, the window opening behaviour was only influenced by the indoor temperature as opposed to the case simulation where many variables affected the window opening behaviour¹. As a result, the indoor temperature was higher and the CO_2 concentration was lower in the case simulation compared to the reference simulation.

¹ Indoor and outdoor temperature, wind speed, CO_2 concentration, indoor and outdoor relative humidity and solar radiation.

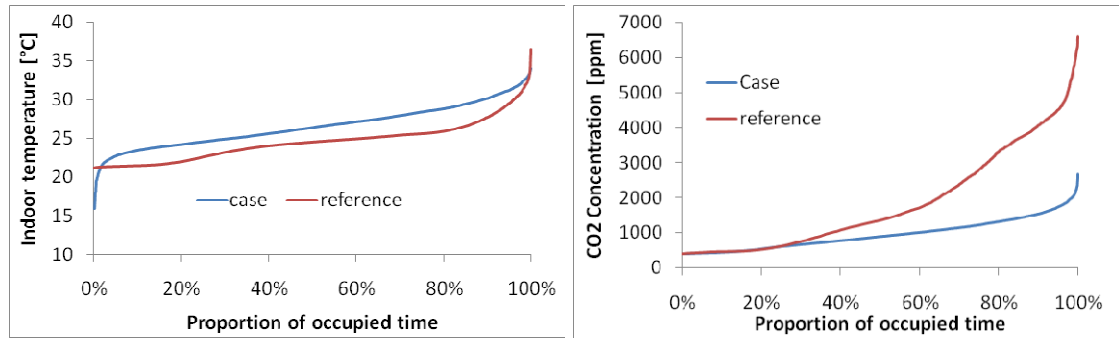


Figure 1: Duration curves for the indoor temperature (left) and the CO₂ concentration (right). The figure shows the duration (in percentage of the time when the room was occupied) the temperature and CO₂ concentration was below a certain level.

Most of the periods with high CO₂ concentrations occurred when the outdoor temperature was low. Since the window opening behaviour was only governed by the indoor temperature in the reference simulation, the windows were not opened even though the CO₂ concentration reached very high values. These values were not achieved in the case simulation since the CO₂ concentration affected the window opening behaviour in such a way as to increase the probability of opening a window with increasing CO₂ concentration.

The higher indoor temperature and the more frequent window opening resulted in a consumption of heat that was 317 % higher in the case than in the reference simulation (table 1). This is remarkably close to the difference of 330 % found by Andersen et al (2005) and again underlines the importance of considering the behaviour of the occupants in the design process of buildings.

Table 1: Results from the simulations with behaviour patterns modelled as described in Andersen et al. (2009) (case) and as a conventional behaviour modelling as reference.

Simulation	Air change rate [h ⁻¹]	Average indoor temperature [°C]	Average CO ₂ concentration [ppm]	Heat consumption [kWh]	Electricity consumption for light [kWh]	Max window opening frequency [opening events/day]
Case	0.90	26.7	882	872.8	868.5	11
Reference	0.61	24.7	1850	274.7	868.6	44

DISCUSSION OF SIMULATION OF BEHAVIOUR PATTERNS

The difference in heating consumption between the simulation with the occupant behaviour model and the reference model was 317 %. If the building had been designed using a behaviour pattern as in the reference, there would have been a very big risk that the actual energy consumption would have been larger than the calculated. The difference in the consumption between the two simulations was primarily due to a low heating set-point in the reference simulation. However, longer periods with open windows also contributed to the increased energy requirement in the case simulation.

Even though the windows were open for a longer time in the case simulation, the reference simulation had the highest daily opening frequency. An opening frequency of 44 opening events/day signifies that the window was opened on 44 occasions during a day. Consequently, the window was also closed 44 times on that day. As a result the window was adjusted 88 times/day or almost every 15th minute throughout the 24 hours. Such excessive window adjustment is regarded as unrealistic.

In the case simulation a random number was continuously compared to the calculated probability of opening or closing a window. This might have resulted in an opening of the

windows even though the environmental variables were within comfort limits. This could have been avoided by only calculating the probability of opening a window if the environmental variables were outside comfort limits. We chose not to implement this approach for several reasons:

First of all the data from the measurements described in Andersen et al. (2009), suggest that windows were sometimes opened based on the time of day rather than environmental variables. If we had chosen only to base window opening on comfort, the time dependent window openings would not have modeled correctly.

Secondly, comfort limits are not easily defined. In thermal comfort, there are several methods of choosing limits for comfortable temperatures and the choice of model would influence the results. Furthermore, the model contains some measures of comfort implicitly. E.g. the probability of opening a window increases with increasing temperature (indoor and outdoor) and with increasing CO₂ concentration. Likewise the probability of closing a window increased with decreasing CO₂ concentration and indoor and outdoor temperature.

CONCLUSION

Using simulated behavior patterns defined based on measurements of behavior of real occupants resulted in an energy consumption for heating that was more than three times as high as when using a more conventional consultant approach. This implies that using the conventional approach might lead to a substantial underestimation of the heating consumption.

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